Towards a Cradle-to-Grave, Mission-Wide Simulation System

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Our Message in a Nutshell

- High-Fidelity simulations of an entire space mission yield immense benefits
- Putting such a simulation together is very difficult
  - Technology is not the issue
- The APGen adaptation to the planned Europa Clipper mission illustrates challenges and solutions
  - It helps to capture corporate knowledge in a Domain-Specific Language (DSL)
  - Reliable “gluing methods” are essential for linking heterogeneous models
- Creating realistic Subsystem models requires very broad knowledge
  - Strive to create reusable patterns which provide uniform access to model information
  - Use hints from Systems Engineering efforts (Integrated Model-Centric Engineering at JPL)
- Successful system integration involves many separate steps
  - Probability of success is small because “centrifugal forces” sink most attempts
  - Back of an envelope estimate of the probability of success: 5%
  - Adopting “centripetal policies” makes success more probable
- We base our final recommendations on insight obtained from our experience

Benefits of High-Fidelity Simulations

- Mission Plan strategy optimization
- Trade studies involving spacecraft configuration, additional instruments, radiator position
- Allocations of energy and data
- Hardware design
- Hardware test plan development
- Operability
- Requirements verification
- Fault sensitivity analysis
- Reusable components for a potential Europa Lander and other future missions

Challenges of System Integration: Lessons Learned

- Lesson 1: it is easy to learn and apply design principles that combine low cost and high probability of success, but it is much more difficult to find guidance in how to integrate systems that were not designed to work together

- Lesson 2: system-wide simulations of a complete space mission require an extremely broad range of domain-specific expertise and experience

APGen adaptation to Europa Clipper

- APGen has been discussed at length at Space Ops conferences in 2006 and 2014 (see references [2] and [3] in the paper)
- Highlights of APGen infrastructure:
  - DSL provides strong but flexible typing, built-in time handling, expressing activity behavior in terms of resource usage and sub-activity creation, ...
  - User-defined library provides for integration of external models
  - Activity hierarchies can be navigated easily
  - Scheduling algorithms allow automated insertion of science and engineering activities into the plan

Subsystem Modeling (1)

- We have identified 8 key subsystems:
  - Deep Space Network (DSN)
  - Guidance, Navigation and Control (GNC)
  - Data
  - Power
  - Geometry
  - Telecom
  - Propulsion
  - Payload

Subsystem Modeling (2)

Element		*Description*	*APGen DSL terminology*
Parameter	Constant	“Constant” whose value may evolve slowly over the life of the mission	Global variable
	Global variable	Allowed to change in time	Global variable
State Variable	Numeric	Varies continuously (e. g. a physical quantity)	Numeric resource
	Discrete	Transitions from one discrete value to the next (e. g. an instrument mode); usually accompanied by a table of allowed transitions	State resource (lists possible states), abstract resource (implements transitions)
Behavior	Goal achiever	Pattern of activities or events designed to meet an objective	Activity type (high level), command (low level)
	Timeline generator	Built-in behavior implemented as a modeling algorithm (possibly external)	Modeling section within activity type definition
Constaint	Goal	constraint imposed on a state over a time interval, usually to achieve a high-level goal	Activity type
	State constraint	passive constraint evaluated during modeling	Constraint
	Goal elaboration	Scheduling constraint used to determine placement of desired activities in the plan	Scheduling algorithm within activity type def.

Subsystem Modeling (3)

Subsystem	Need for Tweakability	Need for Evolvability	Need for Integrability
DSN	Low	Low	Moderate (e. g. export a multi-mission model)
GNC	Low	High (May need to include or emulate FSW)	High (GNC influences many activities)
Data	High (Instrument design and integration evolves over time)	High	High (Instrument teams may design their own data models)
Power	High	Moderate	High (everything onboard the S/C needs or provides power)
Geometry	Moderate (flexibility required in Phase A trade-off studies)	Low	High (everything onboard the S/C has a mounting point)
Telecom	Low	Low	Moderate (needed in activity scheduling)
Propulsion	Low	Low	Low
Payload	High (Instrument behavior evolves from Phase A to C)	High	High (Instrument teams may design their own models)

Why Integration Efforts Fail (1)

ISO-OSI Model

Realm	*Layer Name*
Application	7. Application
	6. Presentation
	5. Session
Data Flow	4. Transport
	3. Network
	2. Data Link
	1. Physical

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Importing a Model into APGen

Realm	*Integration Step*
Modeling Engine	7. Subsystem Synchronization
	6. Setting/Querying of global variables
	5. Modeling run API
User-Defined Library	4. Configuration Management API
	3. Session control AP
	2. External API wrapped into server API
External Model	1. Library or Server

Why Integration Efforts Fail (2)

Exporting a Model from APGen

Realm	*Integration Step*
Modeling Engine	1. Export parameters
	2. Export state variables
	3. Export high-level goals
Scripting Language	4. Modeling command API
	5. File control API
Modeling Server	6. Network access protocol (e. g. XmlRpc, HTML/ReST)
	7. Library or Server

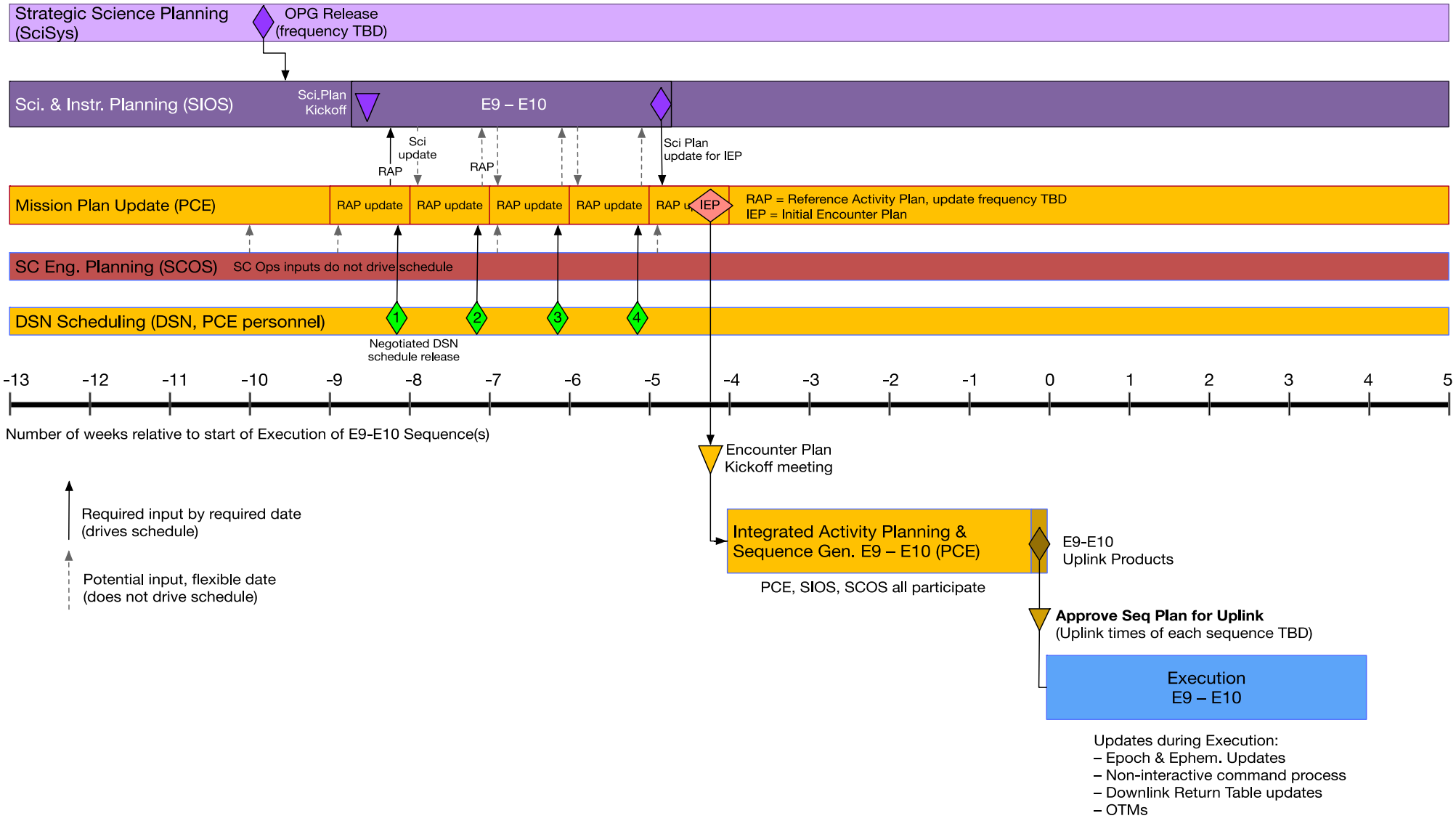
Why Integration Efforts Fail (3)

- Total number of steps required: 7 (export) + 7 (import) = 14
- Simple probability model
  - Assume 90% probability of success for each step
  - Assume all steps are independent of each other
- Resulting probability of success: $(0.90)^{14}=0.0523$
- How can we improve this?

Why Integration Efforts Fail (4)

Characteristic	Description
Centrifugal Characteristics	Organizations do not spontaneously cooperate with other organizations and tend to protect their independence
	Talented individuals often have a preference for their own solutions over approaches that require cooperation with an outside group
Centripetal Characteristics	Project management can state and enforce a modeling methodology that emphasizes system-level integration from the beginning, thus turning model integration into a “corporate goal” and empowering integration efforts
	Project personnel exposed to the benefits of system-wide integration from the very beginning see the concrete advantages of integration, which encourages participation in integration with no need for prodding from anyone

Towards Success (1): Operational Requirements



Towards Success (2): Web-based Access

- Web-based access will have to be provided, which requires setting up the simulation engine as a server or pool of servers capable of supporting a team of users.
- The web interface will have to provide users with the ability to modify the adaptation on the fly, such as the details of scheduling constraints for science activities.
- The system model will have to provide easy-to-query archiving storage, allowing planning personnel to store their plans in association with the changes they made to scheduling constraints.

Towards Success (3): Increased Fidelity

Provide tools to make APGen-based infrastructure available to a wider circle of model designers:

- Provide a streamlined integration process for the Europa Clipper configuration of the APGen model
- Provide an IDE for the APGen DSL similar to those currently available for established languages such as C++ and Java
- Provide a model debugger which allows APGen adapters to zero in on causes of unexpected behavior without having to become an expert in APGen internals

Final Recommendations

- Turn the simulation engine into a modeling server or pool of servers
- Provide web access to the simulation engine and to key aspects of the behavioral and constraint models
- Train mission personnel in the art of subsystem integration by teaching the methodology learned during Europa Clipper model development
- Last but not least, strive to adopt the centripetal characteristics listed earlier:
  - Set and enforce integration guidelines with active management support
  - Use early integration to get user buy in as benefits become obvious